Feed-Forward IMC Applied on Load Frequency Control in Power System

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

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Master of Technology
Electronics and Instrumentation Engineering

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Master of Technology in Electronics and Instrumentation Engineering

Submitted By

Abhishek Kumar

Under Supervision of

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CERTIFICATE

This is to certify that the project entitled, "**Feed-Forward Internal Model Control applied on Load Frequency control in Power System**" submitted by **Abhishek Kumar** is an authentic work carried out by him under my supervision and guidance for the partial fulfilment of the requirements for the award of **Master of Technology** in **Electronics and Instrumentation Engineering during session 2012-14** at **National Institute of Technology, Rourkela.** A bona fide record of research work carried out by him under my supervision and guidance. The candidate has fulfilled all the prescribed requirements.

The Thesis which is based on candidate's own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a Master of Technology Degree in Electronics and Instrumentation Engineering.

Date : (Prof. T. K. Dan)

Place: **Dept. of Electronics and Comm. Engineering**

National institute of Technology Rourkela

ACKNOWLEDGEMENT

I am grateful to The Department of Electronics and Communication Engineering, for giving me the opportunity to carry out this project, which is an integral fragment of the curriculum in M. Tech program at the National Institute of Technology, Rourkela. I would like to express my heartfelt gratitude and regards to my project guide, Prof. T. K. Dan, Department of Electronics and Communication Engineering, for being the corner stone of my project. It was his incessant motivation and guidance during periods of doubts and uncertainties that has helped me to carry on with this project. I would like to thank Prof. S. Meher, Head of the Department, Electronics and Communication Engineering Dept., for his guidance, support and direction. I am also obliged to the staff of Electronics and Communication Engineering Department for aiding me during the course of our project. I offer my heartiest thanks to my friends for their help in collection of data samples whenever necessary. Last but not the least; I want to acknowledge the contributions of my parents and family members, for their constant and never ending motivation.

Abhishek Kumar

(212EC3153)

Dedicated to my Respected Parents Vinod Kumar and Usha Devi, and Lovely Brother Amit Gupta and Sweet Sisters Nilam and Abhilasha.

ABSTRACT

In an interconnected power system, both area frequency and tie-line power interchange fluctuation occurs frequently due to system parameter uncertainties modelling error and environmental disturbance. The objective of load frequency control (LFC) is to bring the steady state frequency error to zero after power demand transient and to minimize the transient deviation in these variables (both area frequency and tie-line power interchange). This paper is based on two degree of freedom (2DF) internal Model Control (IMC) with feed forward controller and IMC filter design, recently developed by Liu and Gao [5] to improve disturbance rejection and to minimize the effect of uncertainties . The feed-forward is added with Saxena and Hote [3] reported work on SOPDT model and results increasing in the robustness of the system.

TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

NOMENCLATURE OF PARAMETERS OF POWER SYSTEM

K_P	Electric system gain
T_P	Electric system time constant (s)
T_T	Turbine time constant (s)
T_G	Governor time constant (s)
R	Speed regulation due to governor action (Hz/p.u. MW)
$\Delta f(t)$	Incremental frequency deviation (Hz)
ΔP_d	Load disturbance (p.u. MW)
$\Delta P_G(t)$	Incremental change in generation output (p.u. MW)
$\Delta X_G(t)$	Incremental change in governor valve position

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Chapter: 1

INTRODUCTION

1.1 Load Frequency Control

In this Generation, almost all equipment runs on electric energy. Electric energy is generated from natural energy is done by power system. A good quality of the electric power system requires both frequency and voltage to remain at fixed or pre defined value during operations. For India, the fixed working frequency and voltages are *50 Hertz and 240 Volts* respectively. The frequency deviates from its standard value due to change of load demands, system parameter uncertainties, modeling error and environmental disturbances. So, load frequency control (LFC) minimizing the frequency deviation errors, rejecting load disturbance and hence LFC maintains power system stability.

For fault tolerance enhancement of the entire power system, these power systems are connected via tie-lines. The usage of tie-line power introduces tie-line power exchange error into the control system problem. Load Frequency Control (LFC) performs efficient and reliable task in power generation in an electrical energy system and tie-line power exchange. The efficient performing roles of LFC for power systems are: 1) maintaining zero steady state errors for frequency deviations, 2) counteracting sudden load disturbances, 3) minimizing unscheduled tie-line power flow between neighboring areas and transient variations in area frequency, 4) coping up with modeling uncertainties and system nonlinearities within a tolerable region, and 5) guaranteeing ability to perform well under prescribed overshoot and settling time in frequency and tie-line power deviation [1], [2]. Thus, LFC can be considered as an objective optimization and robust control problem.

Reasons for regulating constant frequency:

(1) The frequency of power system is directly proportional to the speed of A.C. motors.

(2) The blades of the turbines may get damaged, if frequencies less than 47.5 Hz or above 52.5 Hz of the power system because turbines run at speeds corresponding to frequencies of power system. So we have to maintain operating frequency is at 50 Hz.

(3) The transformer gives better performance on the rated frequency (i.e. 50 Hz). The density of flux increases in the core when frequency declines to the rated frequency at constant voltage system and hence the transformer core jumps into the saturation region.

(4) With reduced frequency the ID fans and FD fans speed decrease in the boiler, and hence power generation decreases and thus multiplying effects occur and may result in tripped off the plant.
(5) In case of nuclear power plant, the reactor may overheat due to reduced flow of coolant as the frequency decline.

To avoiding the above consequences, it is necessary to maintain constant frequency as soon as possible so that the affected area may be reconnected to the main power system.

1.2 Thesis Objective

In power generation system, change in frequency occurs frequently due to load changes and other disturbance. So we have to regulate the frequency (i.e., $\Delta f = 0$) and make better power generation system. This project work is based on Load Frequency Control in Power System using Feed-Forward Internal Model Control to hold constant frequency and to minimize the effect due to any load change on power system.

Therefore the objectives of the load frequency control (LFC) are

- Regulate the frequency constant ($\Delta f = 0$) due to any load change and other uncertainty. Each area must work on absorbing the effect against any load change such that frequency does not deviate.
- The pre-specified value of power flow through tie-line should be maintained by each area.

1.3 Literature review

In paper [3], S.*Saxena and Y. V. Hote*, proposed work is concentrated on model order reduction to second order transfer function from third order transfer function and disturbance rejection of single-area power plant by load frequency control via internal model control. The following techniques for model order reduction are used.

1) Pade approximation [4]
2) Routh Approximation [5]

The above techniques are used to make simple transfer function and two degree of freedom internal model control (2DF IMC) are applied on simplified reduction models. The filter parameters for IMC are determined from the simplified reduction models and IMC filter design, recently developed by Liu and Gao [6] is used for better response and good disturbance rejection.

In paper [7], *W.Tan*, proposed work is based on PID tuning on second order plus dead time (SOPDT) model that is approximated model of single–area power plant third order system. The PID is calculated from simplified 2DF IMC controller by using Maclaurin series.

In paper [8], *Wen Tan, Horacio J. Marquez, Tongwen Chen*, projected work on unstable systems with time delays by modifying IMC structure. This modified IMC structure suggests new tuning parameters.

In paper [9], *Y. Wang , R. Zhou , C. Wen,* proposed a robust controller which is implemented on the Riccati-equation approach for controlling the load frequency of the power system.

In Thesis [10], *Yao Zhang,* worked on load frequency control of multi-area power system by using Active disturbance rejection control (ADRC) technique.

1.4 Thesis outlines

This thesis is having content on Load frequency Control using Feed-Forward IMC. This thesis has number of chapters.

The first chapter introduces about Load frequency control and its existing solutions.

The second chapter understands us about the basic theory on IMC and Feed forward IMC.

The third chapter is about single-area power generations system.

Final chapter is showing the response at measured disturbance input of power system.

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Chapter: 2

INTERNAL MODEL CONTROL AND FEED-FORWARD IMC

2.1 One–degree of freedom (1DF) IMC

Internal Model control (IMC) introduces methods for designing feedback controllers by comparing with process model and to compel the output of a naturally stable process to (1) take action in a desired manner to a set point change, and (2) reject or minimize the effects of disturbances that penetrate directly into the output of process.

IMC structure given in Fig. 2.1 is one degree freedom controller. It consists IMC controller Q(s), the plant to be controlled G(s), and the internal process-model $G_M(s)$. The difference between the outputs of G(s) and $G_M(s)$ known as an error that represents the effect of disturbance D(s) in the real plant if exists.

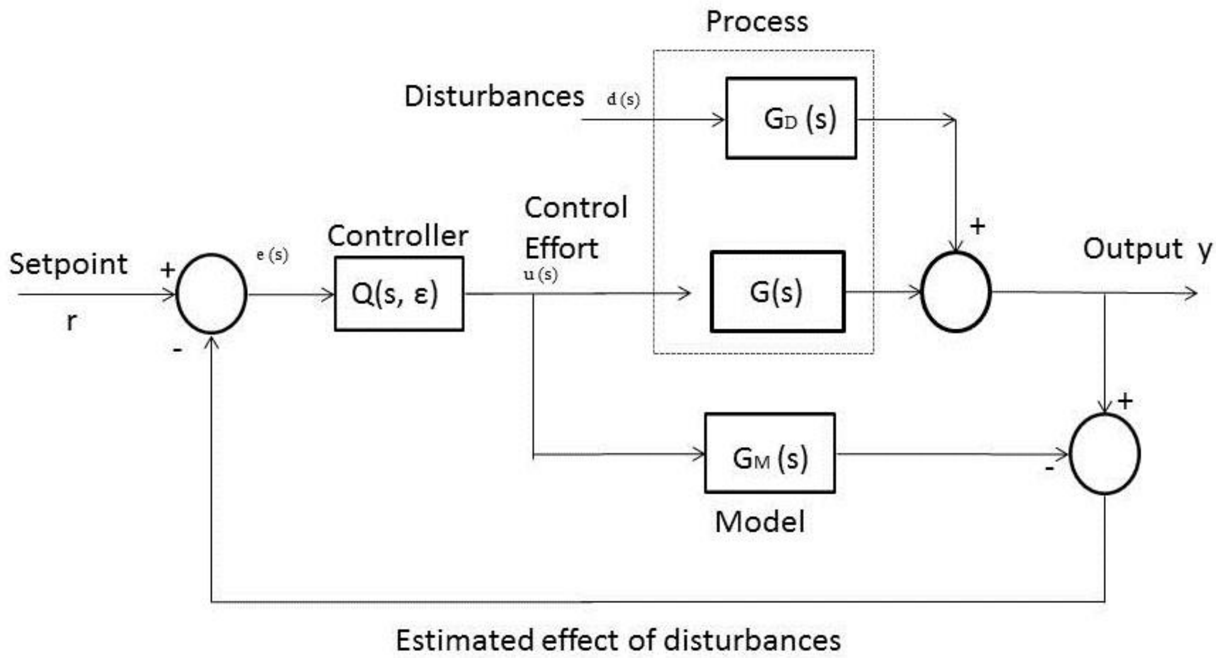

Fig. 2.1 Basic IMC Structure

2.1.1 Transfer Function

The Transfer function of closed loop feedback control system is the ratio of forward gain (G(s)) and one plus of multiple of feedback gain H(s) and forward gain G(s).

i.e.,

$$\frac{y(s)}{r(s)} = \frac{G(s)}{1+G(s)H(s)}$$

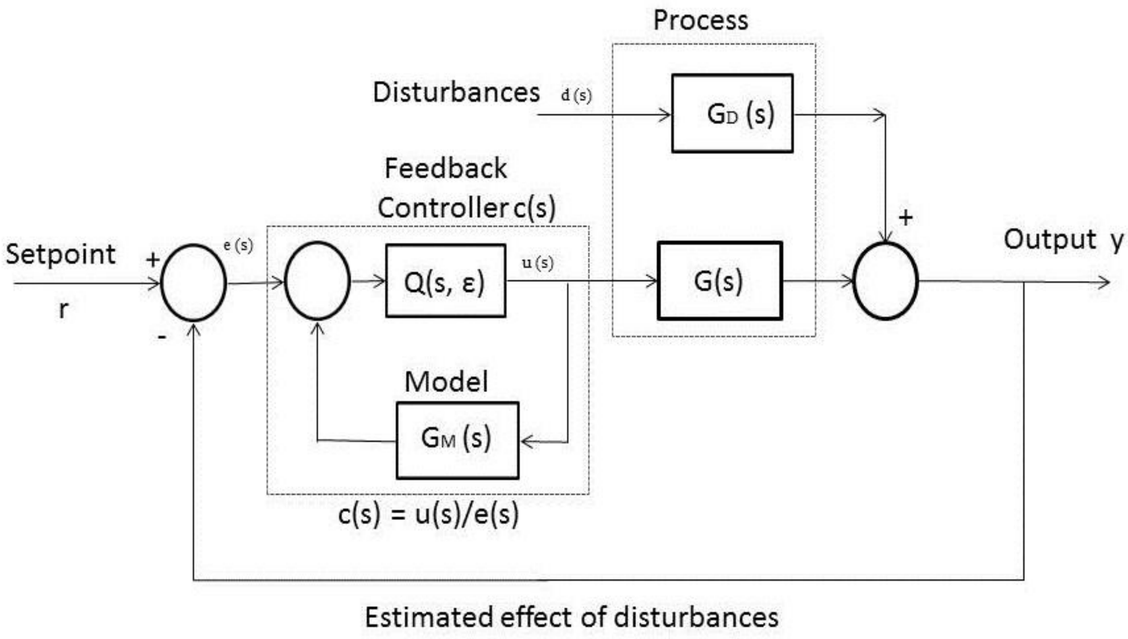

Fig. 2.2 Alternate IMC structure

For the feedback controller c(s) of fig.2.2, the given rule is

$$c(s) = \frac{u(s)}{e(s)} = \frac{Q(s)}{1-Q(s)G_M(s)} \qquad (1)$$

The input-output relationship in IMC system for fig.2.2 are given by

$$\frac{y(s)}{r(s)} = \frac{G(s)c(s)}{1+G(s)c(s)} \qquad (2)$$

$$\frac{y(s)}{d(s)} = \frac{G_D(s)}{1+G(s)c(s)} \qquad (3)$$

$$\frac{u(s)}{r(s)} = \frac{c(s)}{1+G(s)c(s)} = \left(\frac{y(s)}{r(s)}\right)p^{-1}(s) \qquad (4)$$

$$\frac{u(s)}{d(s)} = \frac{-G_D(s)c(s)}{1+G(s)c(s)} = \left(-\frac{y(s)}{d(s)}\right)c(s) \qquad (5)$$

Putting eq.(1) into eq. (2)and eq. (3)and we get,

$$y(s) = \frac{G(s)Q(s)r(s)}{1+(G(s)-G_M(s))Q(s)} \qquad (6)$$

$$y(s) = \frac{(1 - G_M(s)Q(s))G_D(s)d(s)}{1 + (G(s) - G_M(s))Q(s)} \tag{7}$$

2.1.2 IMC Design [12]

IMC controller Q(s) design is done by following steps:

1) Model Factorization

$$G_M(s) = G_{M+}(s)\ G_{M-}(s) \tag{8}$$

2) IMC controller

$$Q(s) = G^{-1}_{M-}(s)\ F(s) \tag{9}$$

in (2), F(s) is a low-pas filter, represented as

$$F(s) = (1+\lambda_1 s)^{-n} \tag{10}$$

where λ_1 = a filter time constant elected to avoid disproportionate noise amplification and to contain modelling errors. And 'n' is an integer, chosen such that Q(s) become proper/semi-proper for physical realization.

$$Q(s) = \frac{D(s)}{N(s)(\lambda_1 s + 1)^r} \tag{11}$$

To avoid disproportionate noise amplification, we suggested that the filter time constant λ_1 be elected so that gain of controller at the high frequency is less than 20 times gain at low frequency. i.e.

$$\frac{Q(\infty)}{Q(0)} \le N \tag{12}$$

where N is between 10 and 20

And hence,

$$\lambda_1 \ge \left(\lim_{s\to\infty} \frac{D(s)N(0)}{20 s^r N(s) D(0)} \right)^{1/r} \tag{13}$$

where r = relative order of N(s)/D(s).

2.2 Two-degree of Freedom (2DF) IMC

1DF IMC scheme is based on pole-zero cancellation. It has very good tracking ability; however, the response to disturbance rejection may be sluggish. So, a trade-off is required, where the performance for load disturbance rejection occurs by sacrificing set-point tracking. To avoid this problem, two different controller Q_D (s) and Q_1 (s) with modified filter [6] are tuned independently, as shown in Fig. 2.3.

2.2.1 Transfer Function

The controller $Q_D(s, \lambda)$ and the setpoint controller $Q(s, \lambda)$ in Figure 2.3 are designed to reject disturbance and to shape the response to setpoint changes respectively.

The output of perfect model y(s) and control effort responses m(s) for Fig.2.3 are given below:

$$y(s) = G_M(s)Q(s,\lambda_1)r(s) + (1 - G_M(s)Q_D(s,\lambda))G_D(s)d(s) \quad (14)$$

$$m(s) = Q(s,\lambda_1)r(s) + Q_D(s,\lambda)G_D(s)d(s) \quad (15)$$

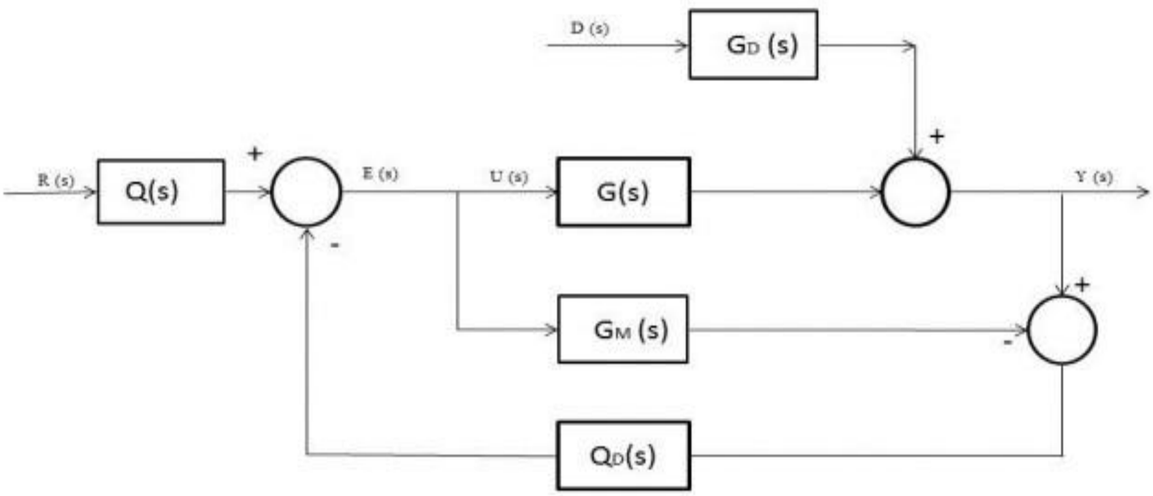

Fig. 2.3 2DF IMC structure

2.2.2 Design of Setpoint Filter, Q(s, λ_1)

The setpoint filter Q(s, λ_1) in Fig.3 is designed by same method in Eq. (9) as setpoint filter for 1DF controller.

2.2.3 Design of Feedback Controller, $Q_D(s, \lambda)$

The transfer function between measured disturbance d(s) and output y(s) for Fig. 4 for perfect model is

$$y(s) = (1 - G_M(s)Q_D(s,\lambda))G_D(s)d(s) \qquad (16)$$

$Q_D(s, \lambda)$ is the composition of two terms, $Q(s, \lambda)$ and $Q_d(s, \lambda)$.

$Q_D(s, \lambda)$ is designed by following steps [8]:

1. $Q(s, \lambda)$ is calculated from Eq. (9).
2. $Q_d(s, \lambda)$ is calculated as

$$\mathrm{Q_d}\left(\mathrm{s},\ \lambda\right) = \frac{\sum_{j=0}^{n} \alpha_i s^j}{(\lambda s + 1)^n}\ ;\ \alpha_0 = 1, \qquad (17)$$

where n = number of poles in $G_M(s)$to be cancelled by the zeros of $(1\text{-}G_M(s)\ Q_D(s, \lambda))$.

3. Select a test value for the filter-time constant λ.

4. The numerical values of α_j is determined though Eq. (18) for each of the n distinct poles of $G_M(s)$ that are to be separated from the disturbance response.

$$(1 - G_M(s)Q_D(s,\lambda,\alpha))\,\big|_{s\,=\,-1/\tau j} = 0; \qquad j = 1,2,\ldots n \qquad (18)$$

where τ_j is the time constant related with the j^{th} pole of $G_D(s)$.

5. Change the value of λ, and do again step 4 until the wanted noise amplification is achieved

The measure of plant/model mismatch can be defined as, closed-loop complementary sensitive function T(s) and multiplicative error $\varepsilon(s)$. where

$$T(s) = Q_D(s)\ G_M(s) \qquad (19)$$

and

$$\varepsilon(s) = \frac{(G(s) - G_M(s))}{G_M(s)} \qquad (20)$$

Example 1: Process response on unit step disturbance [12]

Process and Models are

$$G(s) = G_D(s) = G_M(s) = e^{-s} /(4s+1)$$

Then, setpoint filter is calculated from Eq. (9)

$$Q_r(s) = (4s +1) / (0.2s +1)$$

By following the steps of designing feedback controller $Q_D(s)$, we get

$$Q_D(s) = (1.19s + 1) (4s +1) / (0.2s +1)$$

The response of 1DF and 2DF IMC of same process is shown below in Fig.2.4. We found that 2DF IMC has better disturbance rejection than 1DF IMC and 2DF is faster than 1DF.

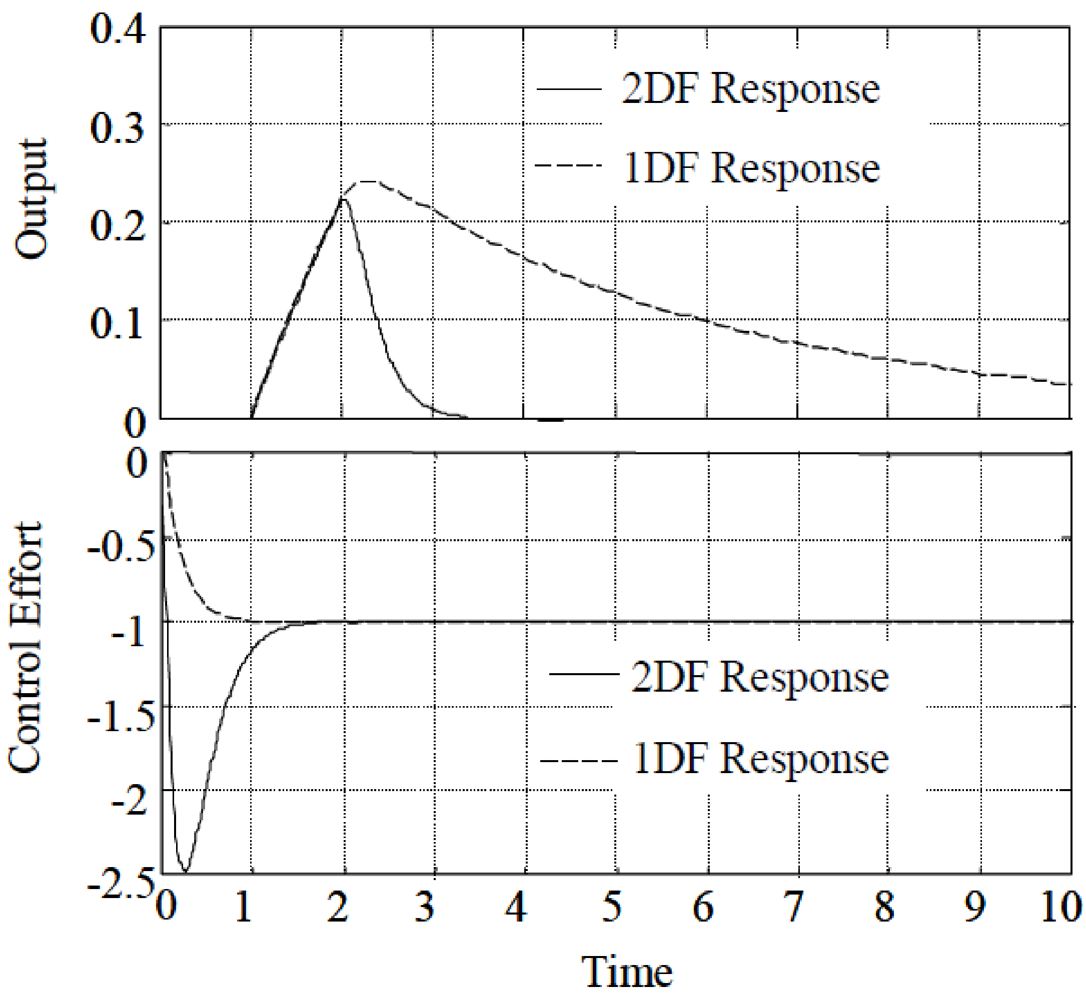

Fig.2.4 1DF and 2DF IMC comparison response to a step disturbance to process of Example 1.

2.2.4 Design of IMC for Unstable Process

A) Internal Stability

Both 1DF and 2DF IMC systems become internally unstable for unstable process. We follow the Morari and Zafiriou (1989) rules are followed when IMC structure is found internally stable.

As per description, a control system is internally stable if we inject bounded input at any point of the control system, produces bounded response at any other point of the control system. Figure 2.5 is same as Figure 2.3, except two inputs u_1 and u_2 are added. Therefore , there are four inputs as setpoint r, disturbance d, and two error inputs u_1 and u_2.

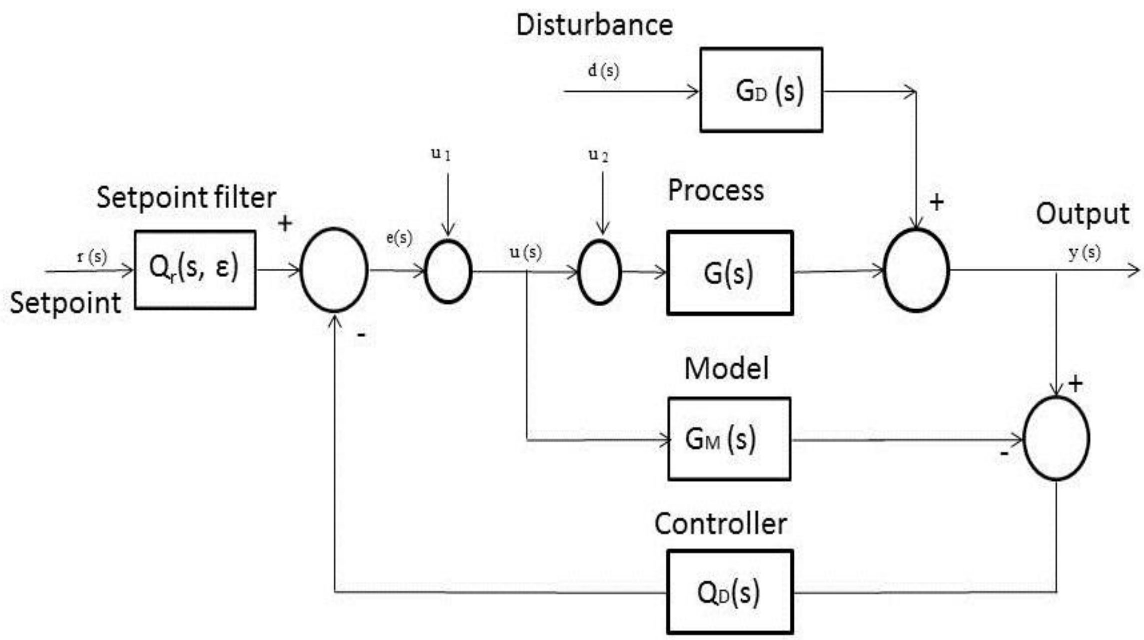

Fig.2.5 2DF IMC system block diagram with additional inputs (u_1 and u_2) for explaining internal stability condition

In order to study the internal stability, it is satisfactory taking the outputs of control system as the outputs of process (y), the output of model (y'), the control effort (u), and the measured disturbances on the process output (d'_e). The transfer functions of input and output for a perfect model are

$$\begin{pmatrix} y \\ y' \\ u \\ d'_e \end{pmatrix} = \begin{pmatrix} GQ & (1-GQ_D)G_D & G & (1-GQ_D)G \\ GQ & GG_DQ_D & G & G^2Q_D \\ Q & G_DQ_D & 1 & GQ_D \\ 0 & G_D & 0 & G \end{pmatrix} \begin{pmatrix} r \\ d \\ u_1 \\ u_2 \end{pmatrix} \tag{21}$$

If, Q, Q_D, G, and G_D are all stable, then all of the input and output transfer functions in Eq. (21) are stable. However, if G, G_D, or Q is unstable, then small change in the input r, d, u_1, and u_2 will cause the output, y, y', u, and d'_e to raise unbound . Hence for unstable process, a 2DF IMC control system design can be simplified into the form of a single-loop feedback control system.

B) Implementation of Single-loop IMC for Unstable Processes

The feedback controller C(s) in Fig.2.6 is

$$C(s) = \frac{Q_D(s,\lambda)}{(1-G_M(s)Q_D(s,\lambda))} \tag{22}$$

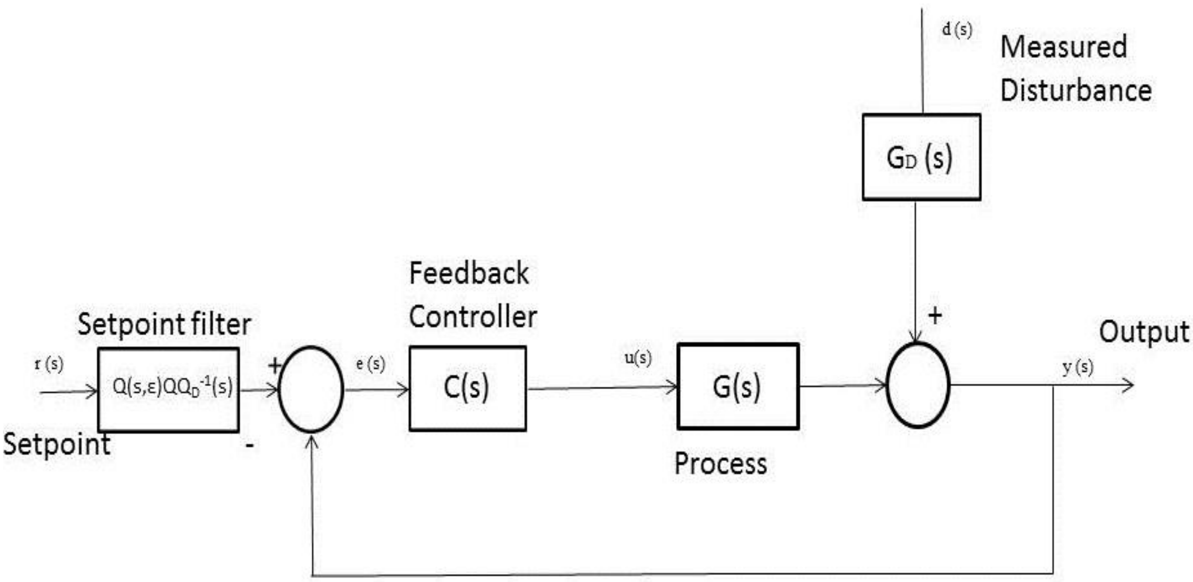

Fig.2.6 Feedback form of 2DF IMC system

The setpoint filter of Fig.2.5 is transformed into the setpoint filter of Fig.2.6 by following correlation. i.e. ,

$$Q(s, \lambda)\, Q^{-1}(s, \lambda) = F(s, \lambda)\, F^{-1}(s, \lambda) \quad (23)$$

where $F(s, \lambda) = (\lambda s + 1)^{-r}$.

For stability, a necessary condition for the control system is that the term $(1 + G_M(s)\, C(s))$ has no right half plane zeros.

The design of the IMC controller has following conditions:

1. $Q_D(s, \lambda)$ must be stable
2. $G_M Q_D(s, \lambda)$ must be stable. This requires that the zeros of $Q_D(s, \lambda)$ cancel the right half plane poles of $G_M(s)$.
3. $(1-G_M Q_D(s, \lambda))\, G_M(s)$ must be stable. This requires that the zeros of $(1-G_M Q_D(s, \lambda))\, G_M(s)$ cancel the unstable poles of $G_M(s)$.

We cannot say C(s) as given in Eq. (22) is stable controller although it is satisfying all condition from 1 to 3.

2.2.5 Modified Filter

Modified filter F'(s) replaces F(s) in Eq. (10) for designing of effective IMC controller and for better disturbance rejection and F'(s) is designed by Liu and Gao [6].

$$F^{'}(s) = \frac{\gamma s^2 + \mu s + 1}{(\lambda s + 1)^x} \quad (24)$$

where x = 3 or 4 , depending upon the requirement to make controller proper.

And hence,

$$Q_D(s) = G_{M-}(s)\, F'(s) \quad (25)$$

On substituting the value F'(s) in (24) to (25), we get

$$Q_D(s) = G_{M-} \frac{\gamma s^2 + \mu s + 1}{(\lambda s + 1)^x} \quad (26)$$

where γ, μ should satisfy the following condition for each pole, p_1 and p_2 of the second – order system:

$$\lim_{s \to -p_i} = (1 - T(s)) = 0, \forall i = 1, 2. \tag{27}$$

where

T(s) = Q_D(s) G_M(s)

$$p_1 = \begin{cases} w_n(\xi - j\sqrt{1-\xi^2}), & 0 < \xi < 1, \\ w_n(\xi - \sqrt{\xi^2 - 1}), & \xi \geq 1 \end{cases}$$

$$p_1 = \begin{cases} w_n(\xi + j\sqrt{1-\xi^2}), & 0 < \xi < 1, \\ w_n(\xi + \sqrt{\xi^2 - 1}), & \xi \geq 1 \end{cases}$$

Putting (8) and (26) in Eq. T(s) = Q_D(s) G_M(s), it gives

$$T(s) = G_{M+} \frac{\gamma s^2 + \mu s + 1}{(\lambda s + 1)^x} \tag{28}$$

Now, from (28), three cases come into existence for G_{M+}(s):

Case 1: when G_{M+}(s) contains delay term only, i.e., G_{M+}(s): $=e^{-\sigma s}$, then take x=4, and by putting (28) into (27), we get

$$\gamma = \frac{p_1 e^{-\sigma p_2}(p_2\lambda - 1)^4 - p_2 e^{-\sigma p_1}(p_1\lambda - 1)^4 - p_1 + p_2}{p_1 p_2 (p_2 - p_1)} \tag{29}$$

$$\mu = \frac{p_1^2 e^{-\sigma p_2}(p_2\lambda - 1)^4 - p_2^2 e^{-\sigma p_1}(p_1\lambda - 1)^4 - p_1^2 + p_2^2}{p_1 p_2 (p_2 - p_1)} \tag{30}$$

Case 2: when G_{M+}(s) contains right hand side poles, then factorize G_M(s) such that G_{M+}(s) has only all-pass term, i.e., G_{M+}(s): = (1-αs) / (1+αs), then take x=3, and by putting (28) into (27), we get

$$\gamma = \frac{\alpha^2 \lambda p_1 p_2 (p_2 + p_1) + (\alpha\lambda^3 + 3\alpha^2\lambda^2) p_1 p_2 + \alpha\lambda(p_2^2 + p_1^2 + p_1 p_2) + (\lambda^3 + 3\alpha\lambda^2)(p_1 + p_2) + 3\lambda^2}{\alpha^2 p_1 p_2 + \alpha(p_2 + p_1 + 1)} \tag{31}$$

$$\mu = \frac{\alpha\lambda^2 p_1^2 p_2^2 + (3\alpha\lambda^2 + 3\alpha^2\lambda) p_1 p_2 - 3\alpha\lambda(p_1 + p_2) + \alpha\lambda p_1 p_2 (p_1 + p_2) + (\lambda^3 + 3\alpha\lambda) p_1 p_2 - 3\lambda}{\alpha^2 p_1 p_2 + \alpha(p_2 + p_1 + 1)} \tag{32}$$

Case 3: when $G_{M+}(s)$ neither contains non-minimum phase term nor delay term, i.e., $G_{M+}(s) = 1$, then it can be considered as a special case of the above mentioned *case 1*. Therefore, on putting σ=0, in Eq. (29) and Eq. (30), it gives

$$\gamma = \frac{p_1(p_2\lambda - 1)^4 - p_2(p_1\lambda - 1)^4 - p_1 + p_2}{p_1 p_2 (p_2 - p_1)} \tag{33}$$

$$\mu = \frac{p_1^{\,2}(p_2\lambda - 1)^4 - p_2^{\,2}(p_1\lambda - 1)^4 - p_1^{\,2} + p_2^{\,2}}{p_1 p_2 (p_2 - p_1)} \tag{34}$$

The major advantages of this controller design scheme are

1) Simplicity
2) Easy practical implementation

2.3 Feed-Forward IMC

Combined feed forward plus feedback control can significantly give better performance over simple feedback control. If there are modeling errors, feed forward control can often reduce the effect of the measured disturbance on the process output. Feed forward control can be implemented with either the classical feedback or IMC structure.

Feed-forward control has economic benefits:

1) Lower operating cost
2) Increased stability of the product due to its more consistent quality.

Feed-forward control is always used along with feedback control because a feedback control system is used to track setpoint changes and to reduce uncertain disturbances that are always present in any real process.

The feed-forward traditional block diagram is shown in Fig. 2.7, and its equivalent block diagram is shown in Fig.2.8 that shows feed-forward controller does not affect the stability of the feedback system. And we can design each system independently.

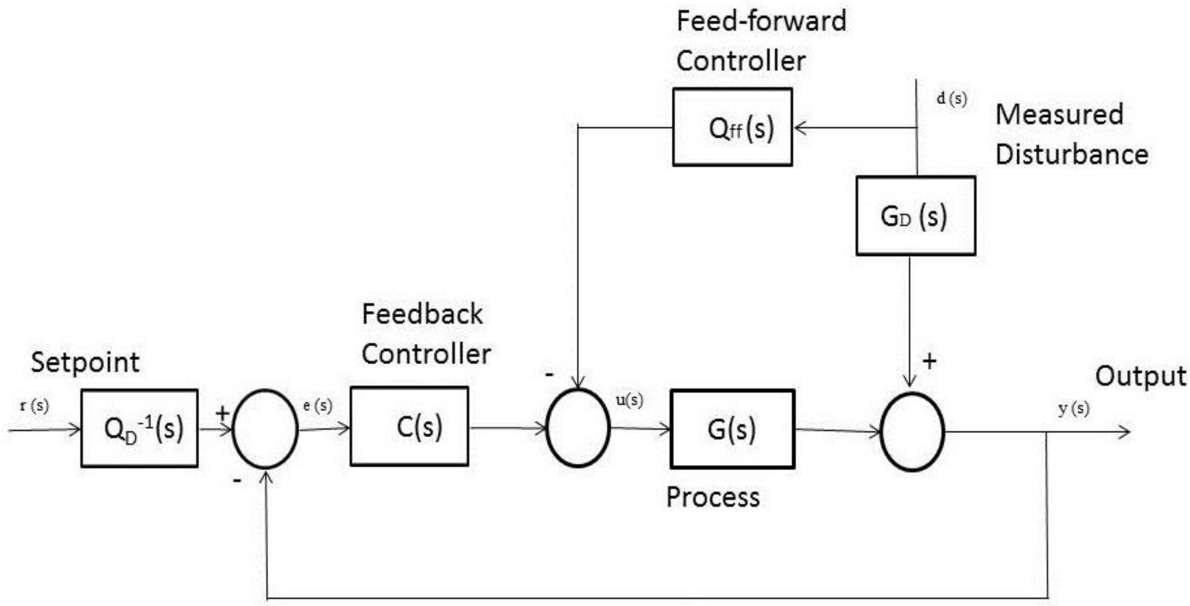

Fig.2.7 Feed-Forward IMC structure

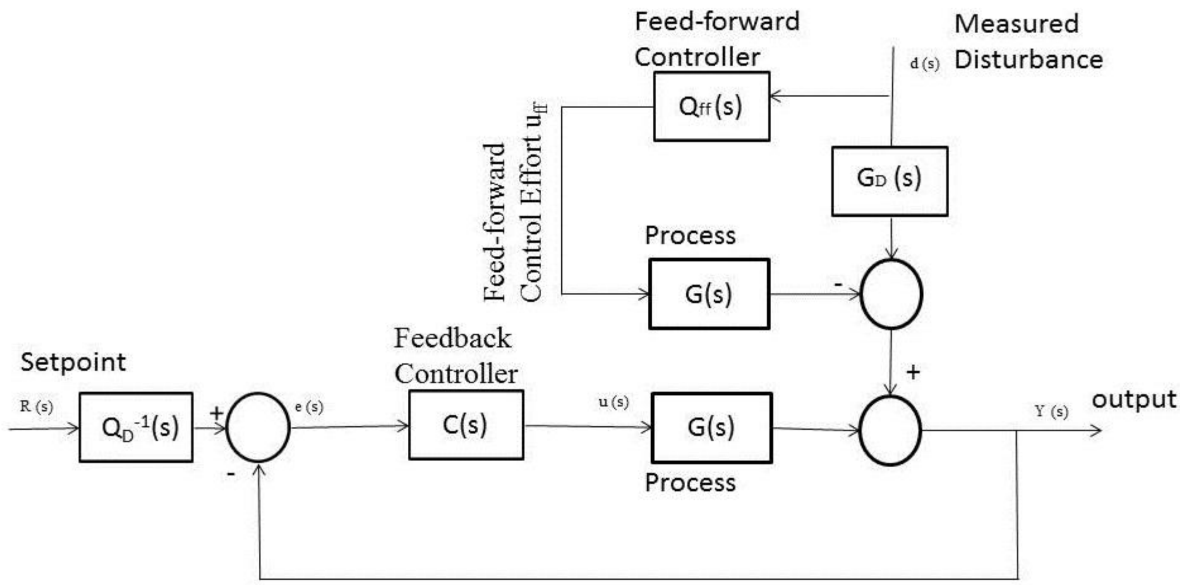

Fig.2.8. Equivalent block diagram of Fig. 8.

The advantages and disadvantages of the feed-forward control are follows:

Advantages

- » Corrective action taken regardless of disturbance source
- » Minimal process information required for controller design
- » PID control is very versatile and usually effective

Disadvantages

- » Corrective action not taken until after the output has deviated from the setpoint
- » Requires measurement of the controlled output
- » Does not allows measured disturbances to be utilized
- » Problematic for processes with large time constants and/or long time delays

2.3.1 Feed-forward Controller Design

The transfer function between process output (y) and the measured disturbance (d) from Fig.2.7 is

$$y(s) = \frac{d}{1+C(s)G(s)} = \frac{(G_D(s) - G(s)Q_{ff}(s))d(s)}{1+C(s)G(s)} \tag{35}$$

The effect of measured disturbance is to be eliminated, we do

$$G_D(s) - G(s)Q_{ff}(s) = 0 \tag{36}$$

Therefore,

$$Q_{ff}(s) = G_D(s)\, G^{-1}(s) \tag{37}$$

We add filter $F_f(s)$ into $Q_{ff}(s)$, every time the relative order of $G_D(s)$ is less or equal to $G(s)$ for reducing the noise amplification. The $F_f(s)$ is given as,

$$F_f(s) = \frac{1}{(1+\varepsilon s)^r} \tag{38}$$

where 'r'is order of the filter, depend on the relative order of $G_D(s)\ G^{-1}(s)$.

2DF IMC controller is simplified into one controller C(s)[8] (feedback controller), (see Eq. (22)). The feedback controller C(s) along with feed-forward controller gives better disturbance rejection and eliminate uncertainties than normal 2DF IMC.

C(s) are defined for (a) SOPDT process model and (b) Tan's [7],[14] proposed SOPDT model.

For (a) $$C^{SOPDT}(s) = \frac{Q_D(s,\lambda)}{(1-G_M(s)Q_D(s,\lambda))} \tag{39}$$

For (b) $$C^{Tan}(s) = K_P + \frac{K_i}{s} + K_d\, s = K_{PID}(s) \tag{40}$$

For SOPDT model, C(s) are normal simplified 2DF IMC controller, but for Tan's SOPDT model C(s) is simplified into PID controller by using Maclaurin series. PID parameters are tuned by Tan's proposed method [7].

2.3.2 Feed-forward Controller Design for Uncertain Processes

A. Gain Variation

Variations of gain in either or both G(s) and $G_D(s)$ can result in a finite value for the steady state effect of the compensated disturbance d_c (see Fig.2.9), on the process output. The feed-forward controller gain (K_f) should be elected to make minimum either the max| $d_c(\infty)$ | or | $d_c(\infty)/d_e(\infty)$ | . Mathematically, it is expressed as

$$d_c(\infty)_{opt} = \min_{K_f} \max_{K_p,K_d} |K_d - K_p K_f| \tag{41}$$

or $$(d_c(\infty)/d_e(\infty))_{opt} = \min_{K_f} \max_{K_p,K_d} |1 - K_p K_f / K_d| \tag{42}$$

The extreme values in Eq. (41) and (42) occur at the simultaneous lower bound of K_d and upper bound of K_p, and at the lower bound of K_p and the upper bound of K_d. The value of feed-forward gain (K_f) that lessen these maxima are those values that make equal the values of the two maxima. i.e.,

For Eq. (42)
$$(K_f)_{opt} = \left(\frac{\max(K_d)+\min(K_d)}{2}\right) \Big/ \left(\frac{\max(K_p)+\min(K_p)}{2}\right), \quad (43)$$
$$\equiv (K_d)_{ave} / (K_p)_{ave}$$

For Eq. (43)
$$(K_f)_{opt} = \left(\frac{\max(K_p/K_d)+\min(K_p/K_d)}{2}\right), \quad (44)$$
$$\equiv (K_p/K_d)^{-1}{}_{ave}$$

The gain of feed-forward controller K_f given by Eq. (44) assures that the compensated disturbance magnitude $d_c(\infty)$ is always less than uncompensated disturbance magnitude $d_e(\infty)$. Therefore feed-forward controller action always improves better the response of the output than output response of system without feed-forward controller.

B. Dead time Variation

We assume that the relative order of the process G(s) is equal to measured disturbance transfer function $G_D(s)$. And the process dead time is greater than measured disturbance dead time, and all time constant are known. The given process is

$$y(s) = K\, g(s) e^{-T_d s}\, u(s) + K_d\, g_d(s) e^{-T_d s}\, d(s) \quad (45)$$

where $g(0) = g_d(0) = 1$, $\underline{T_p} \le T_p \le \overline{T_p}$, $\underline{T_d} \le T_d \le \overline{T_d}$, $\underline{K} \le K \le \overline{K}$, $\underline{K_d} \le K_d \le \overline{K_d}$

The feed-forward controller and calculated dead time are given by

$$q_f(s) = K_f\, g_d(s) e^{-\Delta s} / g(s) \quad (46)$$

where
$$\Delta = \frac{(\overline{T_d} + \underline{T_d}) - (\overline{T_p} + \underline{T_p})}{2} \equiv (T_d)_{ave} - (T_p)_{ave} \quad (47)$$

When 1DF feed-forward compensation is not perfect for a process with dead time than we use a 2DF feed-forward controller for that process.

Example [12]: G(s) = K $e^{-T_p s}$ /(s+1); $0.8 \leq K, T_p \leq 1.2$

$$G(s) = K_d e^{-T_d s}/(4s+1); \quad 0.8 \leq K_d, T_d \leq 1.2 \tag{48}$$

Then, $q_f(s)$ is

$$q_f(s) = K_f (4s+1)/(s+1) \tag{49}$$

The feed-forward controller given in above Eq. has a zero dead time, because the difference between $(T_d)_{ave}$ and $(T_p)_{ave}$ is zero. (see Eq. (47)).

The graph shown in Fig. 2.9 shows the effect of worst case of the above given process. For K_d = 1.2 and K = 0.8, the feed-forward controller gain is '1' and for reversed case (i.e K_d = 0.8 and K = 1.2), the K_f =0.923.

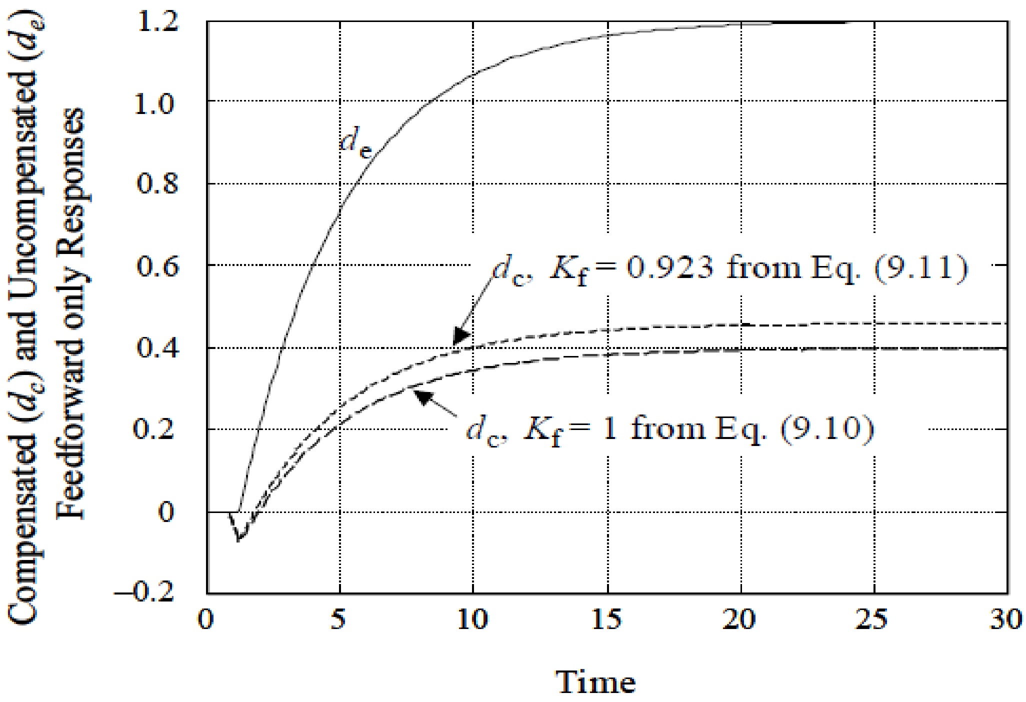

Fig.2.9 response of feed-forward controller to a unit step input

2.4 PID Controller

PID is a combination of three controller 1) Proportional Controller (P) 2) Integral Controller (I) and 3) Derivative Controller (D). The PID controller has had long history of use and it is very effective and most efficient controller in every age. The PID controller are shown below Fig. 2.10.

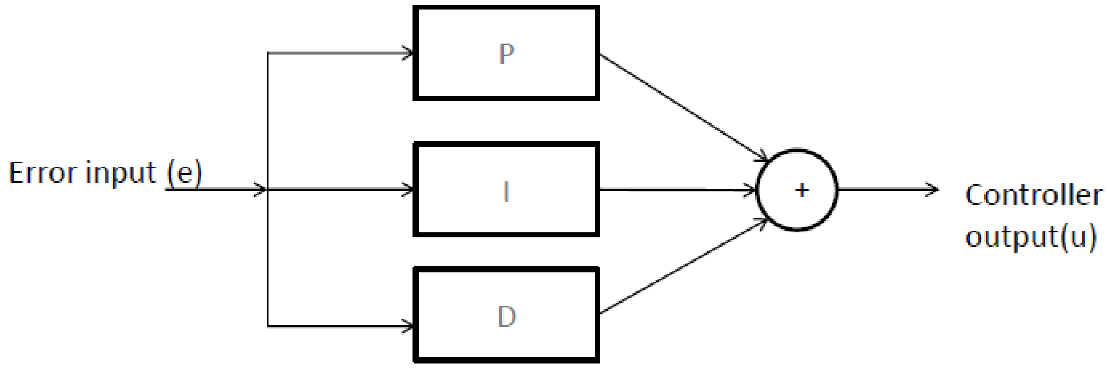

Fig. 2.10 PID Controller

The basic formula of PID controller in Laplace term is

$$C^{PID}(s)=K_p+\frac{K_i}{s}+s\,K_d \tag{50}$$

where

K_p = Proportional Controller , the output controller ‘u’ is proportional to error input ‘e’. In time domain it is represented as

$$u(t)=K_p\,e(t) \tag{51}$$

K_i / s = Laplace representation of integral controller, the output of controller ‘u’ is integration of error input ‘e’. It is represented in time domain as

$$u(t)=K_i\int e(t)\,dt \tag{52}$$

Integral controller is used to eliminate the offset error occurs due to proportional controller.

K_d s = Laplace representation of derivative controller, the output of controller ‘u’ is derivative of error input ‘e’. It is represented in time domain as

$$u(t) = K_d \frac{d}{dt} e(t) \tag{53}$$

Generally, Derivative controller is used to reduce transient time .

In Industries PID Controller structure is chosen on heuristic behaviour od PID terms are described in Table 1. [13]

TABLE: 1

Tuning effects of PID Controller on Step tracking and Disturbance rejection

	Setpoint tracking tuning at step reference		**Disturbance rejection tuning at constant load disturbance**	
	Transient State	**Steady State**	**Transient State**	**Steady State**
P	Rise time decrease when increasing $K_p > 0$	Offset error going down with increasing $K_p > 0$	Rise time decrease when increasing $K_p > 0$	Offset error going down with increasing $K_p > 0$
K_i	Wide range of response types	Eliminates the offset error	Wide range of response types	Eliminates steady state offset errors
K_d	It can be used to tune response damping	No effect on steady state error	It can be used to tune response damping	No effect on steady state error

Important Features of PID Controller

- Wide available and simple in use.
- Three tuning parameters to make the system stable.

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Chapter: 3

SINGLE-AREA POWER PLANT FOR LFC DESIGN

3.1 Single–area Power Plant

The single area power plant for LFC design made of four subsystems is shown in Fig. 3.1 i.e.

1. Governor G_g (s) with dynamics:

$$G_g(s) = \frac{1}{(1+T_g s)} \tag{54}$$

2. Non-reheated turbine G_t (s) with dynamics:

$$G_t(s) = \frac{1}{(1+T_t s)} \tag{55}$$

3. Load and Machine G_p (s) with dynamics:

$$G_p(s) = \frac{1}{(1+T_p s)} \tag{56}$$

4.1/R is the droop characteristics a kind of feedback gain to improve the damping properties of the power system.

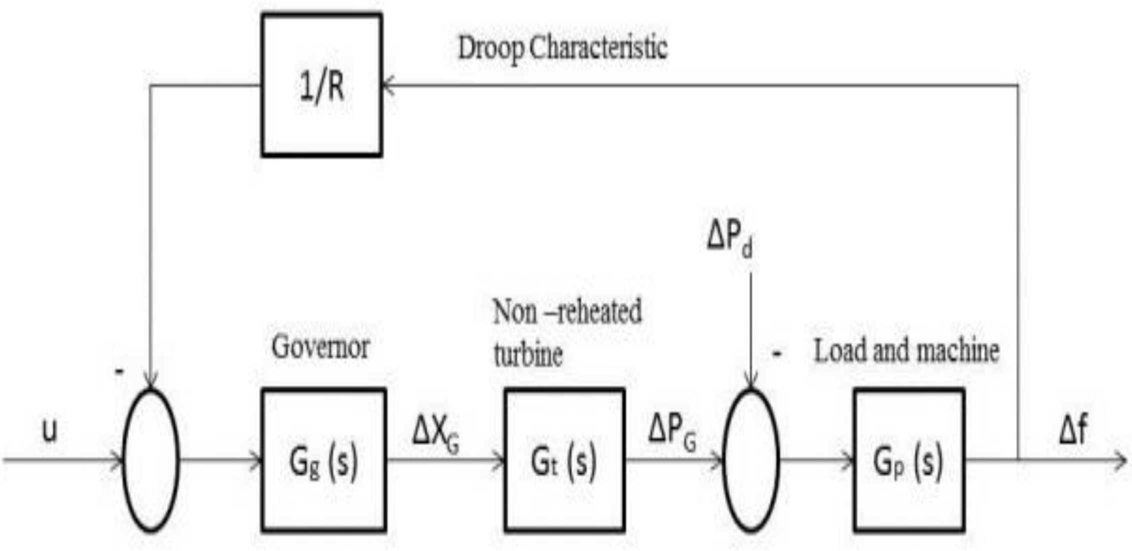

Fig.3.1 Linear Model of a single-area power system

The feedback gain is used in power system is known as droop characteristics and it is used to improve the damping properties of power system, and it is generally represented as 1/R and connected before load frequency control design. So there are two ways for LFC design, i.e.,

1) Design controller $K'_{PID}(s)$ for the power system without droop characteristic, and then subtract 1/R from $K_{PID}(s)$. i.e.,

$$K'_{PID}(s) = K_{PID}(s) - 1/R \tag{57}$$

2) Design controller $K_{PID}(s)$ directly for the power system with droop characteristic.

We are working on Load frequency control (LFC) design with droop characteristic. And analyse the effect of uncertain parameters and disturbance on LFC design with droop characteristics.

3.2 LFC Design with Droop Characteristic

As shown in Fig.3.1, from Eq. (54), (55) and (56), we get overall transfer function of the single-area power plant, i.e.,

$$\Delta f = G(s)u(s) + G_D(s)\Delta P_d(s) \tag{58}$$

where $G_D(s)$ is

$$G_D(s) = \frac{G_p(s)}{1 + G_g(s)G_t(s)G_p(s)/R} \tag{59}$$

and G(s) is

$$G(s) = \frac{G_g(s)G_t(s)G_p(s)}{1 + G_g(s)G_t(s)G_p(s)/R}$$

$$G(s) = \frac{K_P}{T_pT_tT_g s^3 + (T_pT_t + T_gT_t + T_pT_g)s^2 + (T_p + T_t + T_g)s + (1 + K_P/R)} \tag{60}$$

The objective of LFC is to minimize the effect on $\Delta f(s)$ due to load disturbance $\Delta P_d(s)$ and other parameter changes by evaluating the control law: $u(s) = -K(s)\ \Delta f(s)$, where $K(s)$ is IMC based compensator to control the power plant $G(s)$.

The physical representation of Load Frequency Control is shown below in Fig. 3.2.

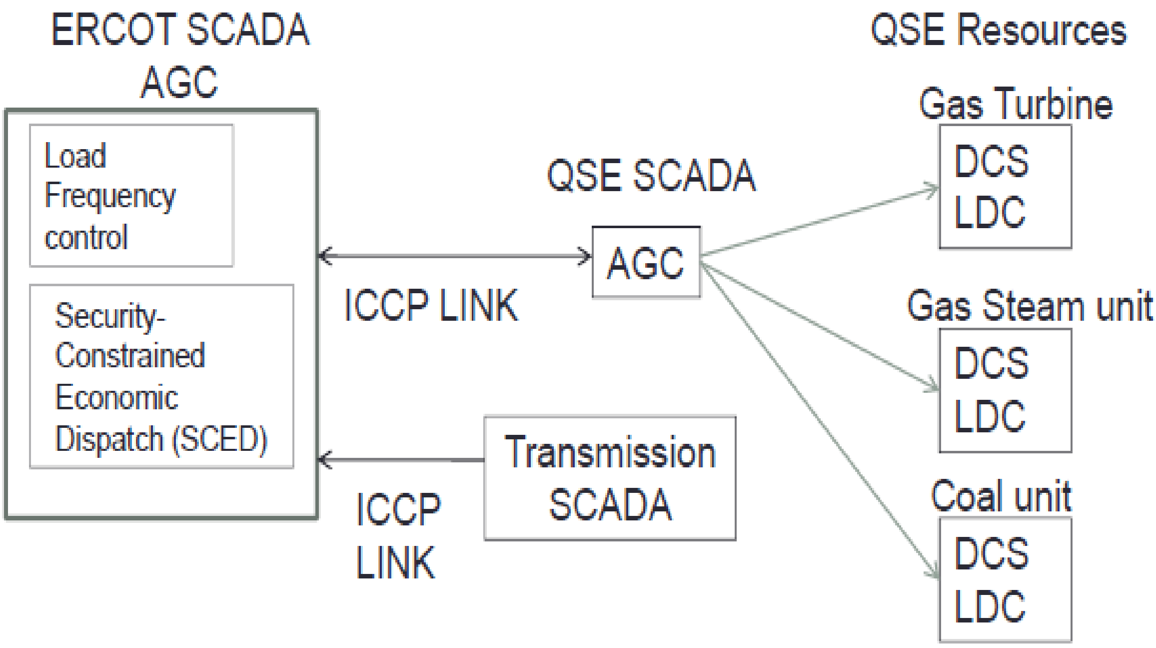

Fig.3.2 Practical Frequency Control System

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Chapter: 4

PERFORMANCE SIMULATIONS AND RESULTS

4.1 Performance Analysis

Consider numerical value of a single–area power system are given as

K_P =120, T_P = 20, T_T = 0.3, T_G = 0.08, R = 2.4 (61)

Using Eq. (61), the plant model G(s), a third-order under-damped system is represented as

$$G(s)=\frac{250}{(s^3+15.88s^2+42.46s+106.2)} \tag{62}$$

In [3] Saxena and Hote reported work, equation (62), a third-order system is approximated into a second-order plus dead-time (SOPDT) model using same parameters value given in (61). The SOPDT model G_{MR}^{SOPDT} and disturbance transfer function $G_D(s)$ are represented by

$$\mathrm{G}_{MR}^{SOPDT}(s)=\frac{18.8268e^{-0.0757s}}{s^2+2.6403s+8.0015} \tag{63}$$

$$G_D(s)=\frac{2.88s^2+45.6s+120}{0.48s^3+7.624s^2+20.38s+51} \tag{64}$$

Now applying proposed method, defining in Eq.(8). By using all pass factorization method, we get

Minimum phase part $\mathrm{G}_{MR-}^{SOPDT}(s)=\dfrac{18.8268}{s^2+2.6403s+8.0015}$ (65)

Non Minimum phase part $\mathrm{G}_{MR+}^{SOPDT}(s)=e^{-0.0757s}$ (66)

From Eq. (26), the corresponding 2DF-IMC $Q_D^{SOPDT}(s)$ is calculated as

$$Q_D^{SOPDT}(s)=\frac{(s^2+2.6403s+8.0015)(0.1649s^2+0.5567s+1)}{18.8267(0.2s+1)^4} \tag{67}$$

where γ, μ, λ, and x are 0.1649, 0.5567, 0.2, and 4, respectively.

In Eq. (22) or (39), the feedback controller is defined and by substituting the Eq. (65) and (67), the feedback controller $C^{SOPDT}(s)$ is

$$C^{SOPDT}(s)=\frac{0.1649s^4+0.992s^3+3.789s^2+7.0947s+8.0015}{s(0.03s^3+0.837s^2+2.206s+6.005)} \tag{68}$$

The author Saxena and Hote worked on model order reduction on third order system by using following model reduction methods 1) Pade Approximation [4], 2) Routh Approximation [5], and 3) SOPDT [3],

The approximated transfer functions of power system and their proposed controller design using same parameters value given in (61) are given as

1. **Pade Approximation**

   The approximated transfers function of the single-area power system:

$$G_{MR}^{Pade} = \frac{-1.191s + 18.92}{(s^2 + 2.708s + 8.043)} \tag{69}$$

   and its 2DF-IMC controller is evaluated from Eq. (27) as

$$Q_D^{Pade}(s) = \frac{(s^2 + 2.708\,s + 8.043)(0.0057\,s^2 + 0.1687\,s + 1)}{(1.191s + 18.92)(0.08\,s + 1)^3} \tag{70}$$

   where γ, μ, λ, and x are 0.0057, 0.1687, 0.08, and 3, respectively.

2. **Routh Approximation**

   The approximated transfers function of the single-area power system:

$$G_{MR}^{Routh} = \frac{18.68}{(s^2 + 3.173s + 7.94)} \tag{71}$$

   and its 2DF-IMC controller is evaluated from Eq. (27) as

$$Q_D^{Routh}(s) = \frac{(s^2 + 3.173\,s + 7.94)(0.1419\,s^2 + 0.5862\,s + 1)}{18.68(0.2\,s + 1)^4} \tag{72}$$

   where γ, μ, λ, and x are 0.1419, 0.5862, 0.2, and 4, respectively

3. SOPDT

The approximated transfers function of the single-area power system:

$$G_{MR}^{SOPDT}(s)=\frac{18.8268e^{-0.0757s}}{s^2+2.6403s+8.0015}$$

and its 2DF-IMC controller is evaluated from Eq. (26) and the feedback controller

$C^{SOPDT}(s)$, respectively as

$$Q_D^{SOPDT}(s)=\frac{(s^2+2.6403s+8.0015)(0.1649s^2+0.5567s+1)}{18.8267(0.2s+1)^4}$$

$$C^{SOPDT}(s)=\frac{0.1649s^4+0.992s^3+3.789s^2+7.0947s+8.0015}{s(0.03s^3+0.837s^2+2.206s+6.005)}$$

where γ, μ, λ, and x are 0.1649, 0.5567, 0.2, and 4, respectively.

4. Tan's SOPDT model

As per Tan's proposed method [7], $C^{SOPDT}(s)$ is changed to PID Controller with the help of Maclaurin series. Hence Tan's model feedback controller is

$$C^{Tan}(s)=0.4036+\frac{0.6356}{s}+0.1832s \qquad (73)$$

There disturbance rejection response for the 2DF-IMC system without feed-forward controller are shown in Fig. 4.1, when setpoint input is zero and measured disturbance input is -10.

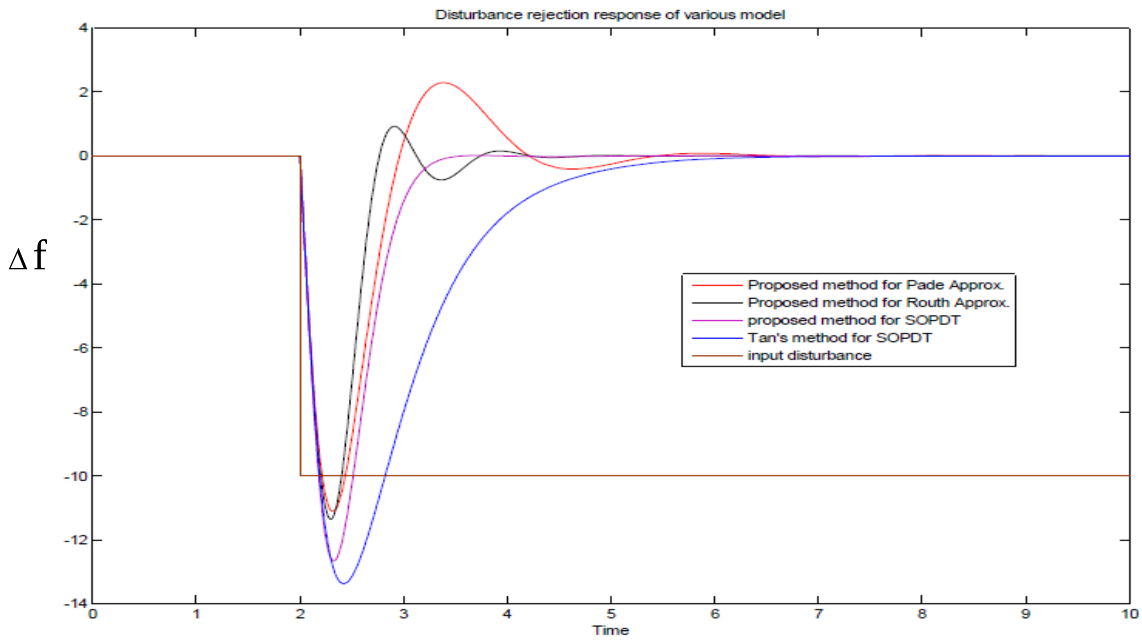

Fig. 4.1 Disturbance Rejection Response at disturbance input '-10' of approximated proposed model

To verify the robustness and performance of a power system model, suppose the parameters of this system vary by 50%,as expressed in [3], and shown in Fig. 4.2 i.e.

$$\Delta_1 = \frac{1}{T_P} \in [0.0331, 0.1] \qquad \Delta_2 = \frac{K_P}{T_P} \in [4,12]$$

$$\Delta_3 = \frac{1}{T_T} \in [2.564, 4.762] \qquad \Delta_4 = \frac{1}{RT_G} \in [3.081, 10.639]$$

$$\Delta_5 = \frac{1}{T_G} \in [9.615, 17.857] \tag{74}$$

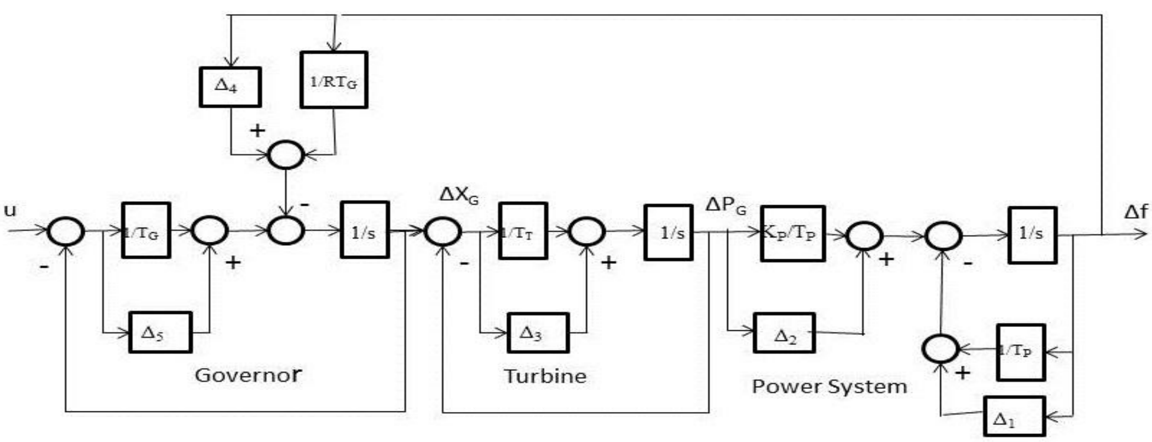

Fig.4.2 Linear model of power system with uncertain parameters [3]

The disturbance rejection response graph of the tuned Feedback controller IMC for upper and lower bounds uncertain system are shown in Fig.4.3 and Fig. 4.4

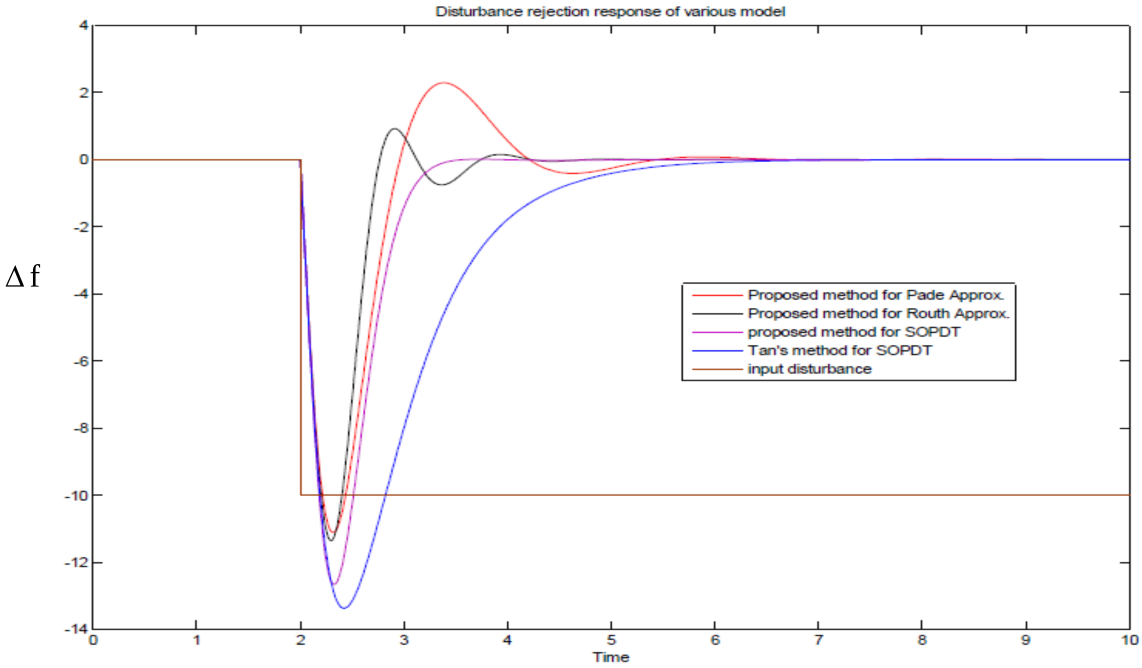

Fig.4.3. Lower Bound Disturbance Rejection Response of Approximated models

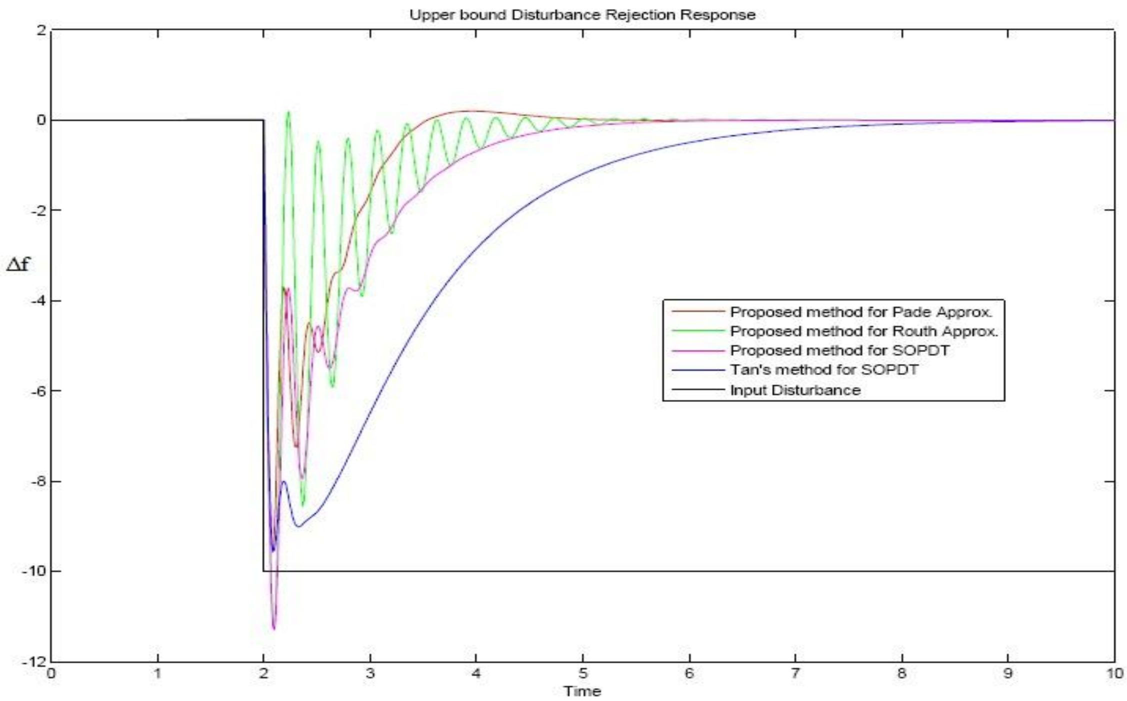

Fig.4.4. Upper Bound Disturbance Rejection Response of Approximated models

For the lower bound and upper bound uncertainty power system, the results of disturbance rejection are shown in above Fig. 4.3 and Fig. 4.4. Hence, we can say that the parameter and controller used for normal system can handle the upper bounds and lower bounds uncertain system and superior performances are achieved compared to the Tan's proposed controller [7] [14]. Thus, the proposed scheme is reflecting robustness of the system.

Our project is based on the extended work on Saxena and Hote works [3]. The brief description of Saxena and Hote proposed work are being defined by above brief definition of model order reduction and graphs of disturbance rejection response for i) normal case (Fig. 4.1) ii) lower bound uncertain (Fig. 4.3) iii) upper bound uncertain (Fig. 4.4).

Our project is working on load frequency control using feed-forward IMC, where we add feed-forward controller to 2DF IMC controller. We have work done on two model i) SOPDT and ii) Tan's SOPDT model.

The approximated second order plus dead time (SOPDT) transfer function of power system is

$$\mathrm{G}_{MR}^{SOPDT}(s)=\frac{18.8268e^{-0.0757s}}{s^2+2.6403s+8.0015}$$

From Eq. (27), the corresponding 2DF-IMC $Q_D^{SOPDT}(s)$ is calculated as

$$Q_D^{SOPDT}(s)=\frac{(s^2+2.6403s+8.0015)(0.1649s^2+0.5567s+1)}{18.8267(0.2s+1)^4}$$

whereγ, μ, λ, and x are 0.1649, 0.5567, 0.2, and 4, respectively.

The feed-forward controller Q_{ff} is

$$Q_{ff}=\frac{(2.88s^2+45.6s+120)(s^2+2.6403s+8.0015)}{18.8268(0.48s^3+7.624s^2+20.38s+51)} \tag{75}$$

From Eq. (37), we have calculated Q_{ff}, but it is not proper. So we add filter to make Q_{ff} proper. The filter constant 'ε' is calculated from Eq. (12) for less noise amplifications. Then we get the value of 'ε'

$$\varepsilon\geq 0.0159 \tag{76}$$

But we take 'ε' = 0.02 .

Therefore the feed-forward controller Q_{ff} is

$$Q_{ff} = \frac{(2.88s^2 + 45.6s + 120)(s^2 + 2.6403s + 8.0015)}{18.8268(0.48s^3 + 7.624s^2 + 20.38s + 51)(0.02s + 1)} \tag{77}$$

This project is worked on two models for LFC using Feed-Forward IMC.

1) SOPDT

From Eq. (63), the feedback controller C(s) for SOPDT model is

$$C^{SOPDT}(s) = \frac{0.1649s^4 + 0.992s^3 + 3.789s^2 + 7.0947s + 8.0015}{s(0.03s^3 + 0.837s^2 + 2.206s + 6.005)}$$

From Eq. (68) and Eq. (77), the feed-forward IMC system for normal SOPDT model is made.

The Simulink model of SOPDT is shown in Fig. 4.5.

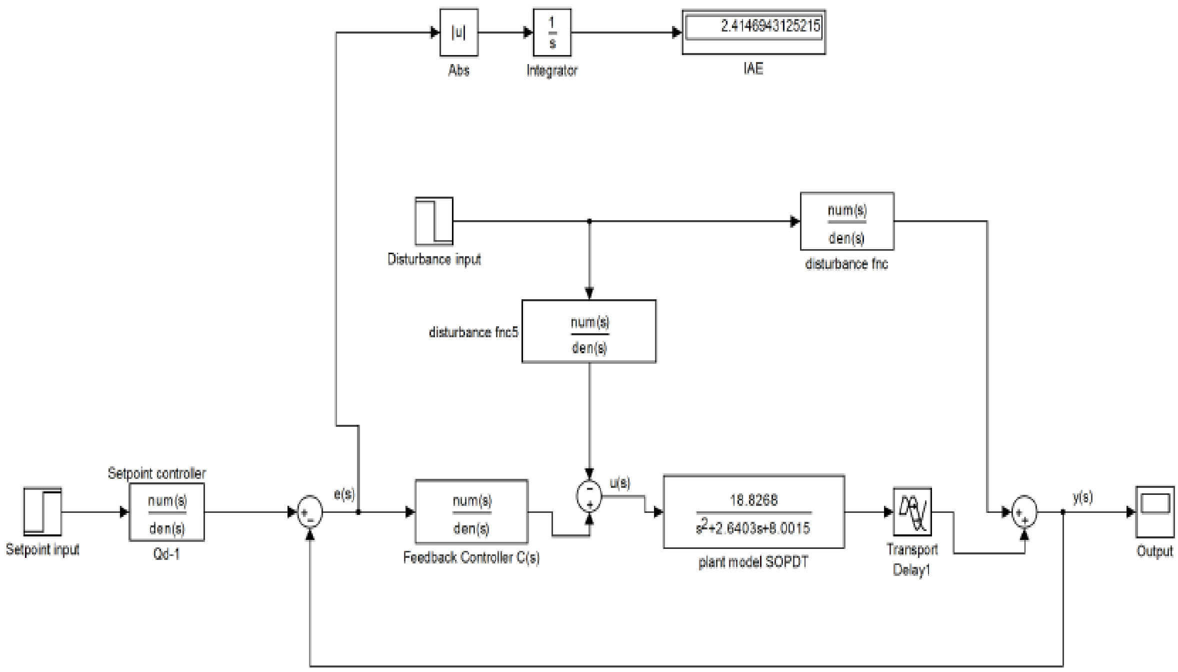

Fig. 4.5 Simulink model of SOPDT

The comparison is shown in Fig. 4.6 defining the effect between Feed-Forward IMC and 2DF IMC for normal SOPDT model and their Integral Absolute Error [14] showing below the Figure 4.6.

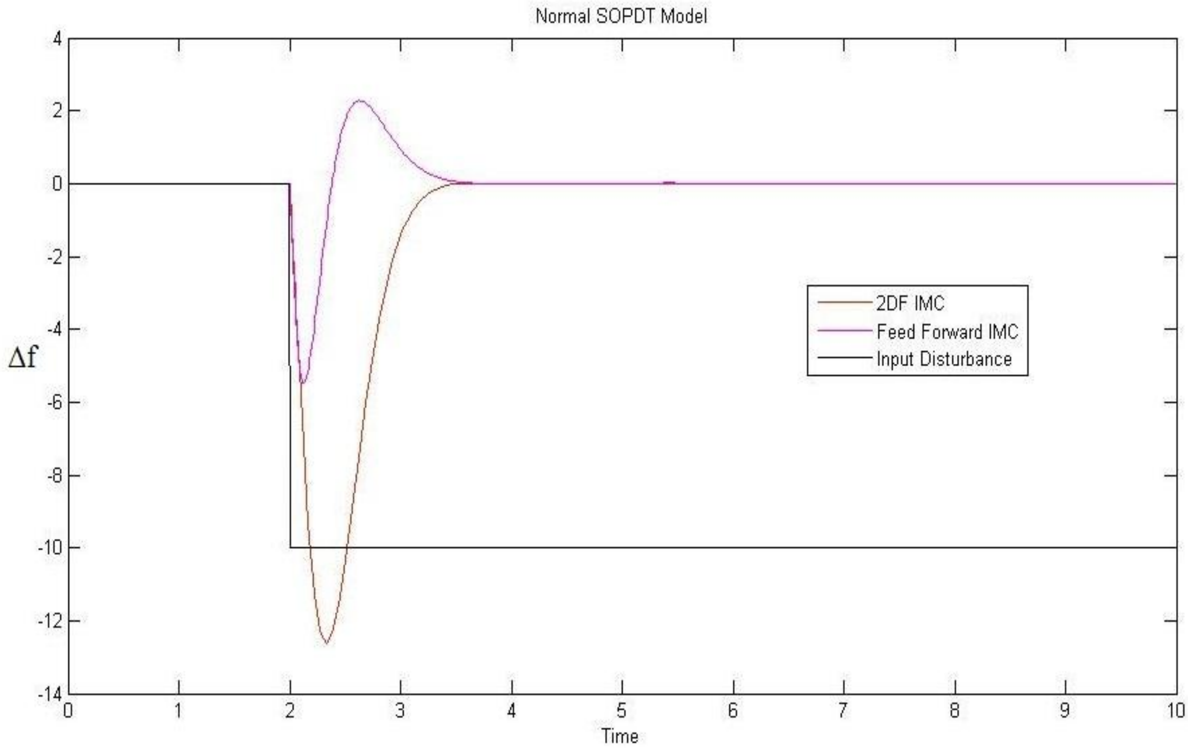

Fig.4.6 Disturbance Rejection Response for SOPDT model in 2DF IMC and Feed-Forward IMC

Integral Absolute Error (IAE)	SOPDT	SOPDT with Feed-Forward
Nominal Case	7.5216	2.4146

2) **Tan's SOPDT model**

The feedback Controller C(s) for Tan's model is PID controller, where PID parameters are calculated with the help of Maclaurin series, From Eq. (68), the feedback controller $C^{Tan}(s)$ for Tan's SOPDT model is

$$C^{Tan}(s) = 0.4036 + \frac{0.6356}{s} + 0.1832s$$

From Eq. (73) and Eq. (75), the feed-forward IMC system for Tan's SOPDT model is made.

The Simulink model of SOPDT is shown in Fig. 4.7.

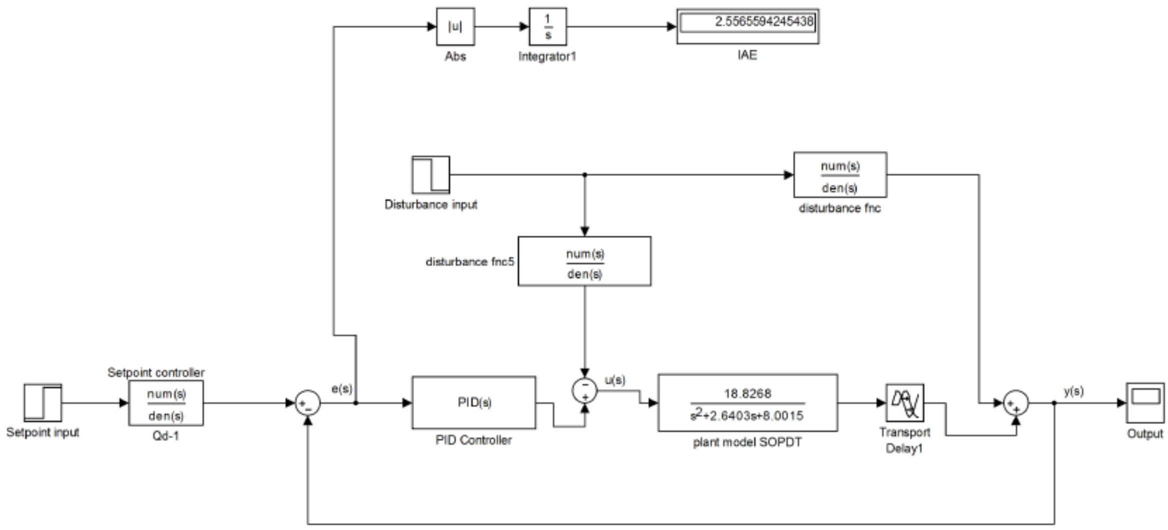

Fig. 4.7 Simulink model of Tan's SOPDT model

The comparison is shown in Fig. 4.8 defining the effect between Feed-Forward IMC and 2DF IMC for Tan's SOPDT model and their Integral Absolute Error showing below the Figure 4.8.

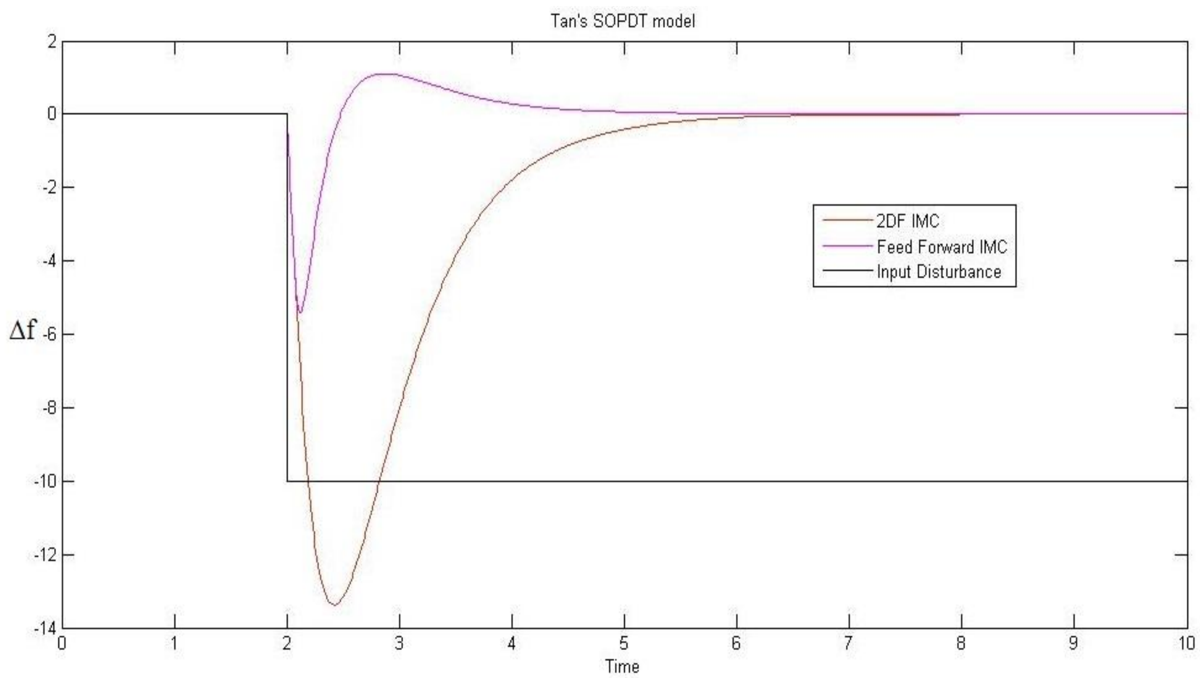

Fig.4.8 Disturbance Rejection Response for Tan's SOPDT model in 2DF IMC and Feed-Forward IMC

Integral Absolute Error (IAE)	Tan's SOPDT model	Tan's SOPDT model with Feed-Forward
Nominal Case	32.297	2.5665

To verify the robustness and performance of a power system model with Feed-forward IMC, increase or decrease the parameters of this system by 50%, as expressed in Eq. (74) .The disturbance rejection response graph of the tuned Feed-forward IMC for upper and lower bounds uncertain system are shown in Fig. 4.9 and Fig. 4.10 for normal SOPDT and Tan's SOPDT model respectively and their Integral Absolute Error showing below the Figure 4.9. and 4.10.

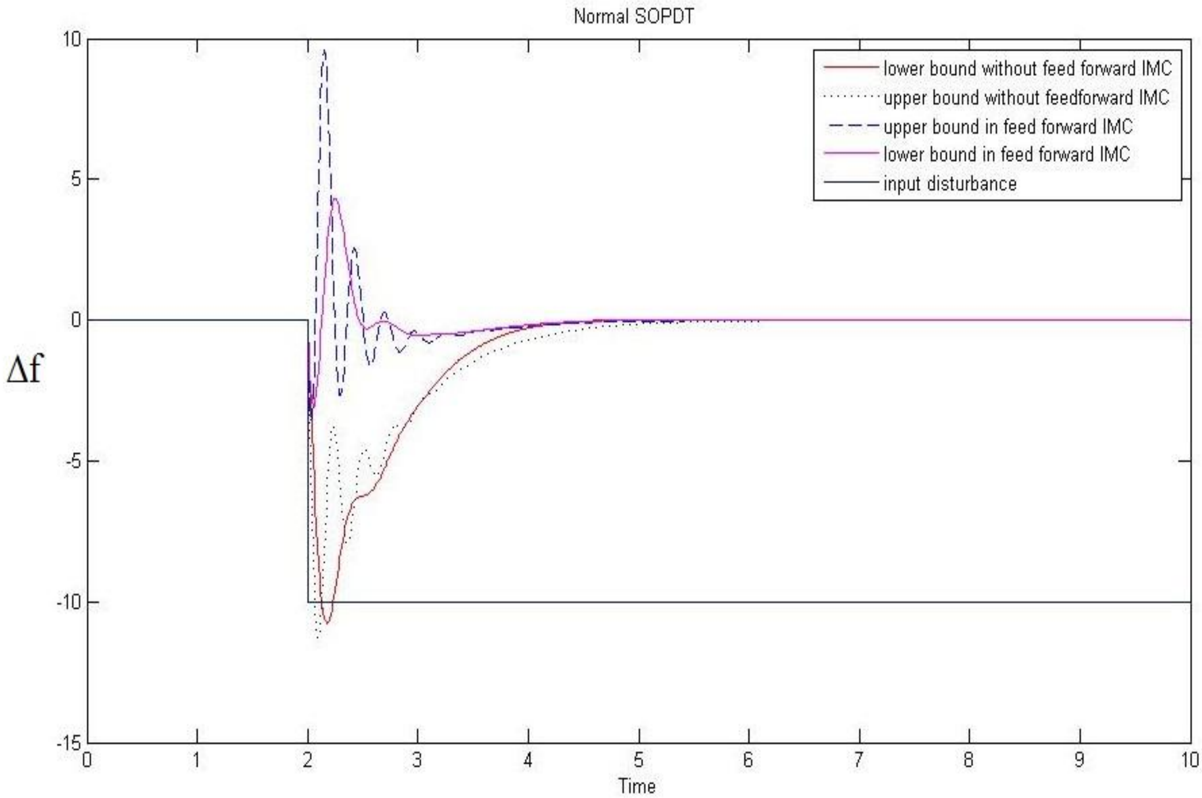

Fig.4.9 Upper and Lower Bound Disturbance Rejection Response for SOPDT model in 2DF IMC and Feed-Forward IMC

Integral Absolute Error (IAE)	SOPDT	SOPDT with Feed-Forward
Upper Bound Uncertain	7.505	2.540
Lower Bound Uncertain	7.540	1.661

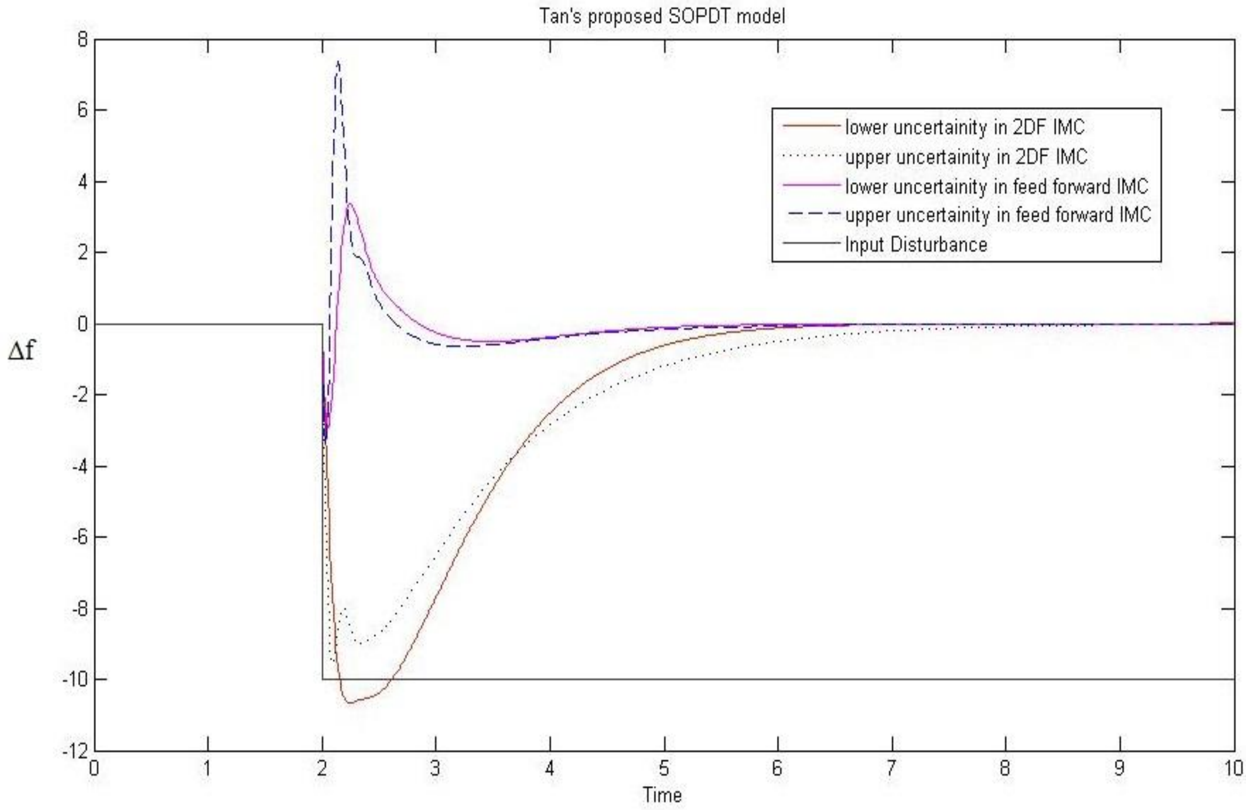

Fig.4.10 Upper and Lower Bound Disturbance Rejection Response for Tan's SOPDT model in 2DF IMC and Feed-Forward IMC

Integral Absolute Error (IAE)	Tan's SOPDT model	Tan's SOPDT model with Feed-Forward
Upper Bound Uncertain	15.72	2.6049
Lower Bound Uncertain	15.7331	2.009

4.2 Comparison and Integral Absolute Error (IAE)

For different values of feed forward filter constant 'ε', remarkable results of disturbance rejection are shown in Fig. 4.11 and Fig. 4.12 for both model i) normal SOPDT and ii) Tan's SOPDT model respectively.

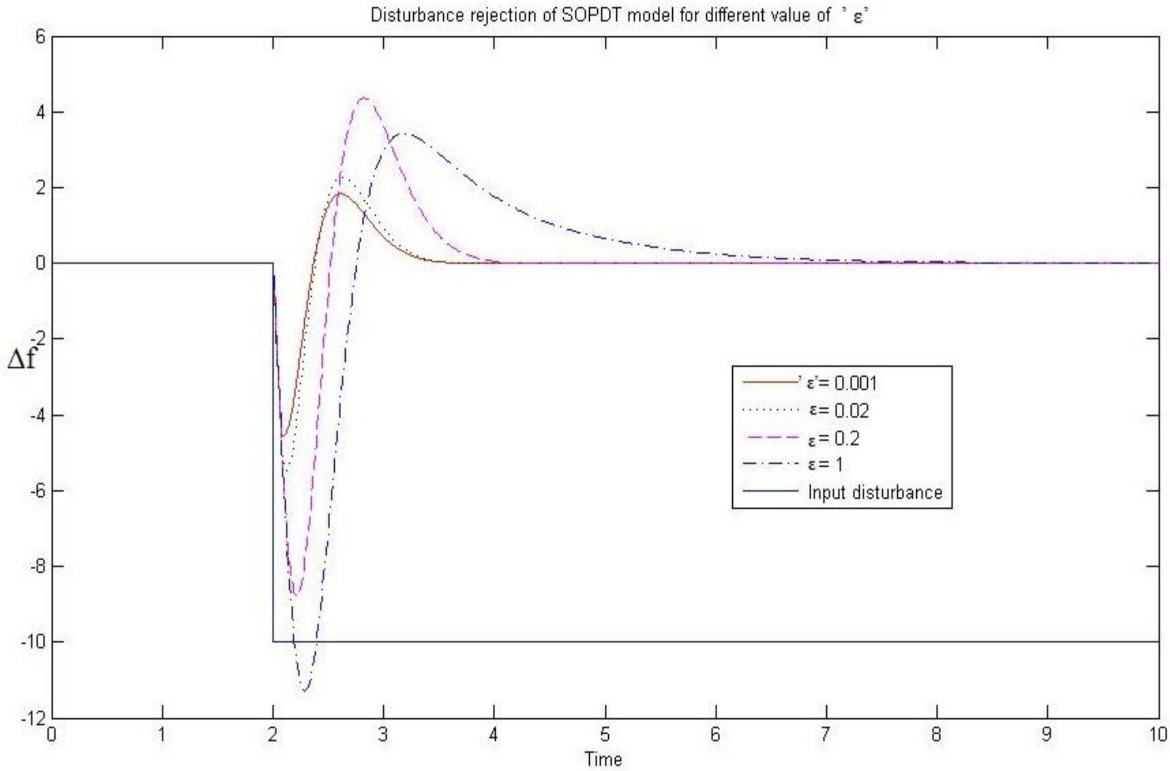

Fig.4.11 Disturbance rejection response at different value of 'ε' for SOPDT model

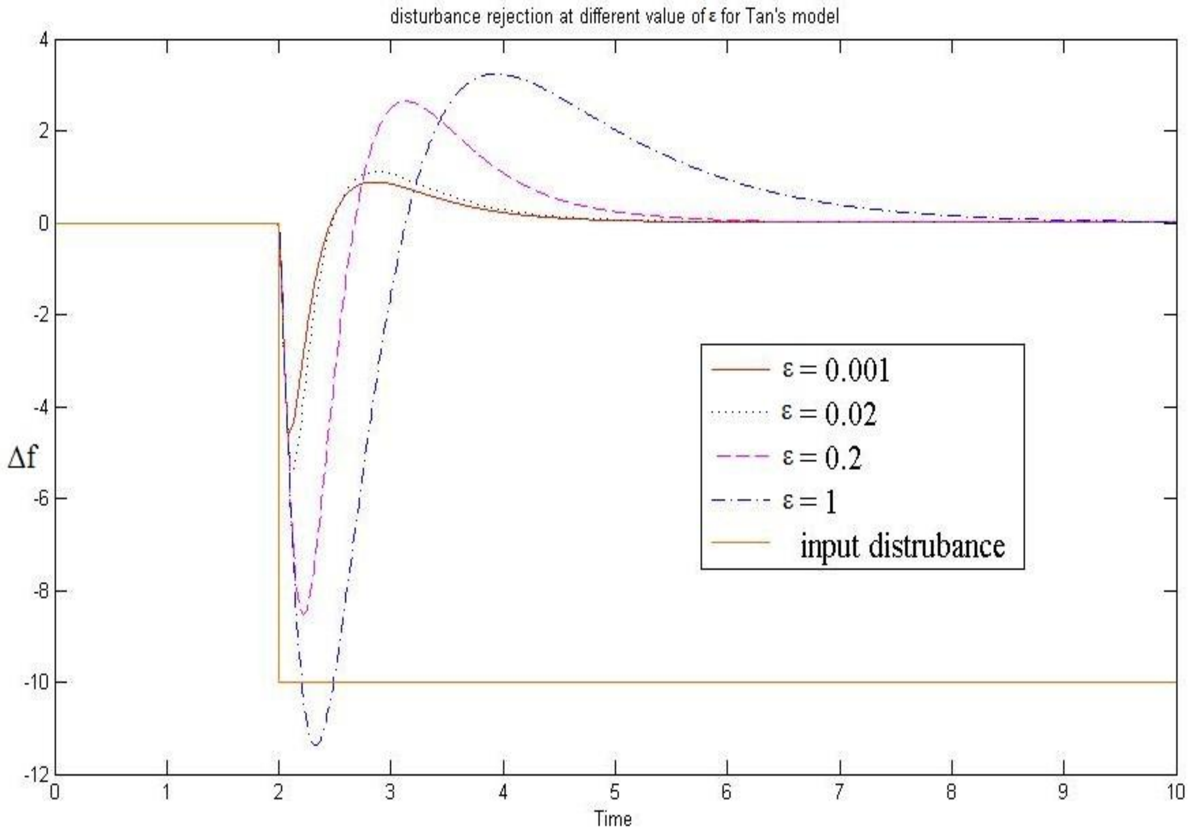

Fig.4.12 Disturbance rejection response at different value of 'ε' for Tan's model

We concluded that filter constant 'ε' should be lie in between ε_1 to λ where ε_1 (Feed-forward filter constant) is minimum limit which is calculated from (12) and λ is 2DF filter constant. If we take 'ε' less than ε_1, there is no remarkable change and if 'ε' > λ, large change is spotted in terms of settling time and Integral Absolute Error (IAE) [14].

IAE at different value of 'ε' are shown in Table 2.

TABLE 2

Integral Absolute Error (IAE) on different value of ' ε'

Model	**$\varepsilon = 0.02$**	**$\varepsilon = 0.2$**
SOPDT model	2.41461	5.54506
Lower bound SOPDT	1.6610	2.47982
Upper bound SOPDT	2.540	1.81193
Tan's model	2.5665	6.503
Lower bound Tan's model	2.009	2.76697
Upper bound Tan's model	2.6049	1.52068

From the Table.2, Integral Absolute Error (IAE) is very less for $\varepsilon = 0.02$ than for $\varepsilon = 0.2$ in all case except upper bound case. If $\varepsilon <= 0.02$, very little change in IAE in comparison of $\varepsilon = 0.02$, but $\varepsilon => 0.2$, large change in IAE is spotted which is seen in Fig.4.11 and Fig. 4.12.

CONCLUSION

LFC Techniques using Feed-forward IMC increases robustness against parameter uncertainties as well as plant/model mismatch and external load change. Feed-forward IMC gives faster and smoother response than 2DF-IMC. Feed-Forward IMC on SOPDT shows better response than Tan‘s SOPDT model. The lower value feed forward filter constant has done better disturbance rejection and also tracks the set point fast. The different value feed-forward filter constant affects disturbance rejection response for both models and also responsible for Integral Absolute Error variations. The limitation of ε (feed-forward filter constant) is concluded for better plant stability and robustness.

Future Work

This thesis is worked on Feed-forward IMC applied on single-area power system. But it may be applied on multi-area power system and we have to analyse the performance and disturbance rejection response at load changes and other uncertainties. We have to investigate efficient IMC based PID tuning parameter methods for both single-area and multi-area system for better performance and for increasing robustness. IMC based Feed-Forward control system may be applied on other power systems such as Boiler Drum control and Furnace control for improving the power plant efficiency.

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